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Original Research

Integrated Environmental Performance Assessment of Basic Oxygen Furnace Steelmaking

Zhigang Jiang[1]*, Hua Zhang[1], Wei Yan[1], Min Zhou[1], Gongfa Li[1], Geng Huang[2]

[1]College of Machinery and Automation, Wuhan University of Science and Technology, 430081 Wuhan, China
[2]Department of Human Resource Management, Wuhan Iron and Steel (Group) Company, 430015 Wuhan, China

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Abstract

Steel enterprises, as one type of major industrial pollution source, have been facing great environmental pressure. Integrating environmental considerations into the steelmaking process is now one of the major priorities of the steel industry. A method for evaluating environmental performance is presented in this paper. The proposed method considers the procedure for environmental performance comparison of design alternatives as a multi-criteria decision-making (MCDM) problem. An integrated environmental index for the steelmaking process is proposed and qualified, utilizing the Chinese Standard (emission standard of waste pollutants for iron and steel industry). The pair-wise comparison approach of the analytic hierarchy process (AHP) is employed for solving the MCDM problem. A case study is used to illustrate how the assessment method may be applied and to demonstrate its applicability.

Keywords: steelmaking process, environmental performance, AHP, integrated assessment

Introduction

During recent years, it has been recognized that environmental emissions of the steelmaking process are a major factor in the global warming effect [1]. The accelerating environmental consciousnesses of individuals, companies, and government entities serve as a driver for steelmakers to focus attention on the environmental performance of their operations. Therefore, environmental considerations should be integrated into the steelmaking process design, and regarded as a first step on the path to continuous environmental improvement.

Environmental performance evaluation of a steel making process has attracted significant attention from researchers. Lin and Polenske applied a process-level input-output model based on reported process data to illustrate how changes in steelmaking can affect environmental aspects in terms of disposal costs [2]. Spengler et al. presented an outranking method for environmental assessment of recycling measures in steelmaking [3]. Lianexay et al. presented an environmental impact assessment method for steel plant construction, considering environmental standards in Thailand, specifically those related to air pollution emissions, ambient air quality, effluent standard, and noise [4]. Xiu et al. established an evaluating method for pollution contributions in the iron and steelmaking process [5]. Haapala et al. presented a process modeling approach to improve the environmental performance of steel manufacturing operations [6]. Vahdat et al. utilized fuzzy logic method to evaluate environmental emissions of iron and steel production in Iran [7]. Kramer et al. developed a new approach to the production of coke that involves reduced environmental emissions and enhanced economics [8]. Although various methods are available in the literature, an effective environmental performance evaluation method including an integrated environmental index is required.

A life cycle assessment (LCA), or "cradle to grave" analysis, has emerged as a powerful analytical tool for envi-

*e-mail: jzg100@163.com

ronmental performance evaluation [9]. Xu et al. adopted an LCA perspective to analyze and reduce greenhouse gas (GHG) emissions in the steelmaking process [10]. Iosif et al. combined a physicochemical modeling approach with LCA thinking, in order to carry out the LCI, (life cycle inventory, a phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle) of classical steelmaking [11]. Tongpool et al. used LCA method to find out how to improve environmental performance of the steel industry in Thailand [12]. LCA essentially seeks to determine the impact of a product or a process on the environment through its entire life cycle from the cradle to the grave. However, it is recognized that the classical approach of assessing LCI takes time, and usually it cannot guarantee the quality of the data that needs be used to predict environmental performance with respect to operational conditions. Li et al. suggested that environmental performance evaluation should be integrated with the steelmaking process design, and work be initiated to create a simple and effective method to evaluate steelmaking from an environmental perspective [13]. Such an evaluation method can identify the major impacts, and provide insight into improvement opportunities.

Motivated by the foregoing discussion, this paper proposes a generic method for evaluating the environmental performance of steelmaking. The conceptual framework for evaluating environmental performance of the industry is introduced. An integrated environmental index is proposed for environmental decision-making, and a detailed procedure for environmental performance assessment based on the AHP is established. Following the presentation of the proposed method for evaluating environmental performance, the method is demonstrated via steelmaking examples.

Methodology Overview

To obtain environmental information during the steelmaking process, a quantitative analysis of environmental performance is highlighted. The method presented in this paper seeks to look at the overall environmental performance, and identify what action(s) to take by evaluating environmental performance. The method comprises the steps of classifying, characterizing, and quantifying the environmental data as shown in Fig. 1.

At the first stage of the assessment, the process data are inventoried. According to the categories of environmental emissions, environmental data are classified, characterized and quantified at the second stage. Finally, an integrated environmental index is obtained by utilizing multiple criteria decision-making (MCDM) analysis. Then the different alternatives are ranked according to the scores for their environmental indices. Moreover, the scores for the evaluated steelmaking process then serve as feedback for process changes or to show how alternative process schemes may be judged [14].

Steelmaking Process Data

Steel is manufactured by the chemical reduction of iron ore using an integrated steel manufacturing process or a direct reduction process. In the conventional integrated steel manufacturing process, iron from the blast furnace is converted to steel in a basic oxygen furnace (BOF). Steel can also be made in an electric arc furnace (EAF) from scrap steel and, in some cases, from direct reduced iron. BOF is typically used for high-tonnage production of carbon steels, while the EAF is used to produce carbon steels and low tonnage specialty steels. An emerging technology, direct steel manufacturing, produces steel directly from iron ore. This paper deals only with the classical route of steelmaking based on the production of hot metal from iron ore, and its conversion to steel in a converter, as shown in Fig. 2.

Inputs for steel production are mainly power and iron or steel raw materials. The outputs are steel products, unwanted products, solid wastes, and emissions to air and to water. The unwanted products such as scrap, slag, and scale can be sold to cement or recycling industries. The emissions to air, e.g. CO_2, CO, SO_x, NO_x, and dust, as well as emissions to water, e.g. oil, grease, chemicals, and suspended solids, may damage ecosystem quality and human health.

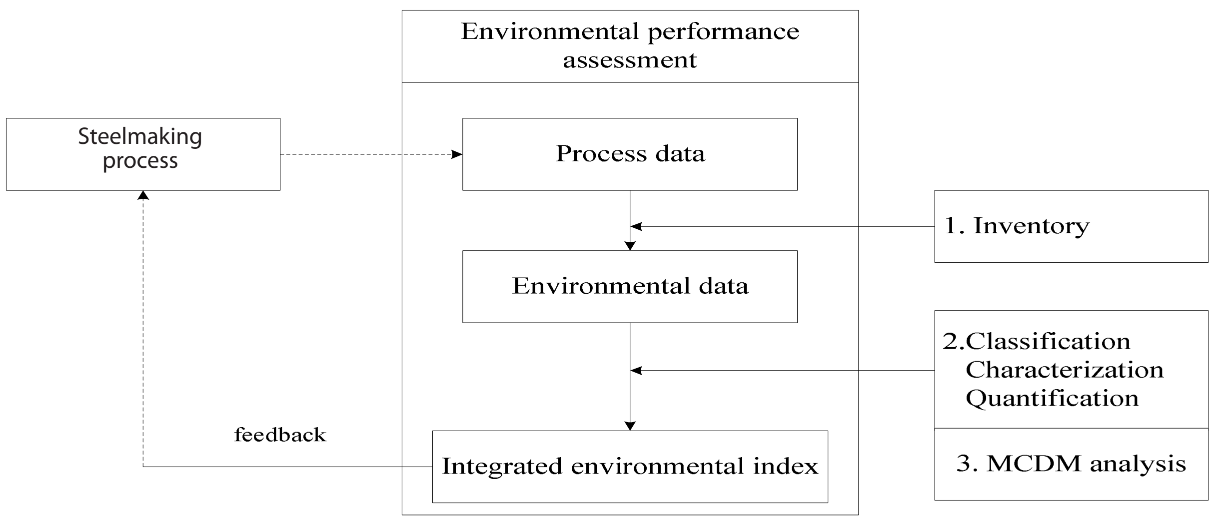

Fig. 1. Conceptual framework for evaluating environmental performance.

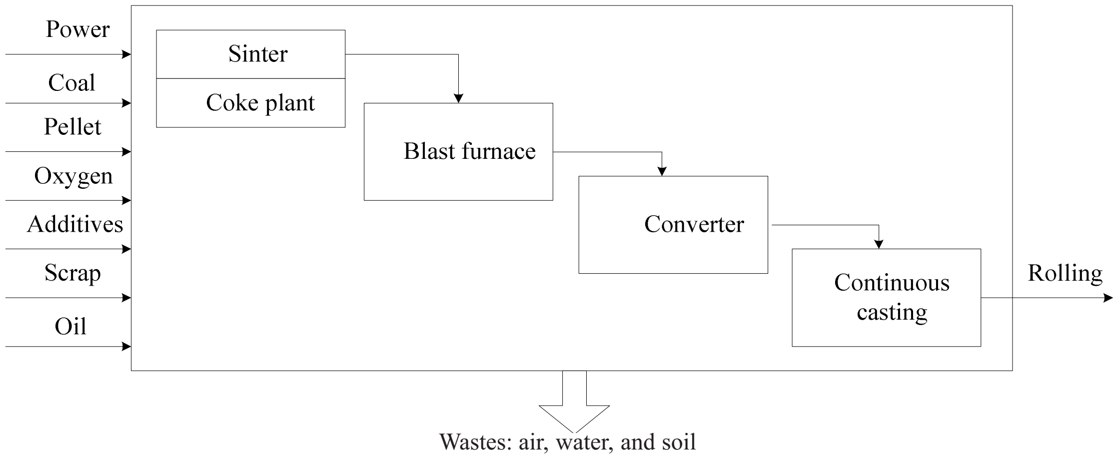

Fig. 2. Schematic description of the steelmaking process.

The input and output data that are collected in a given situation depend on the goal and scope of the study, and may include a mixture of measured, estimated, and calculated data. The collected data makes it possible to perform a total analysis for the steelmaking process to assess the effect of a change in the operation practice for the different process.

Integrated Environmental Index

As has been noted, conducting an evaluation requires the development of a listing of all the criteria and measurements, as well as the different forms of each (e.g. dust and airborne emissions). In general, emission wastes can be identified as solids, liquids, and gases.

According to different types of output data, a hierarchical (performance – criteria – measures) structure for evaluating environmental performance is presented, as shown in Fig. 3. At the coarsest level, a single goal (characterizing the performance of the steelmaking process) is presented. At the next level, the performance is divided into three criteria. At the lowest level, the performance within each criterion is described by specific measurements. It is at this level where the performance can be evaluated.

For measurements with widely disparate units, directly combining them is difficult. Normalizing them is an effective way to put all the measurements on an equal footing and make them dimensionless. The measurements can be calculated using the following equation:

$$d = \frac{u_r}{u} \quad \text{or } d = 1 - \frac{u}{u_r} \tag{1}$$

...where u is the value of the emissions and u_r is the reference value for the measurements. The form of the normalization equation will provide larger d values when wastes or emissions are reduced.

It is noted that u_r is often defined by the company, but may also be dictated by government regulations or standards. For example, the Chinese standard HJ/T 318-2006:

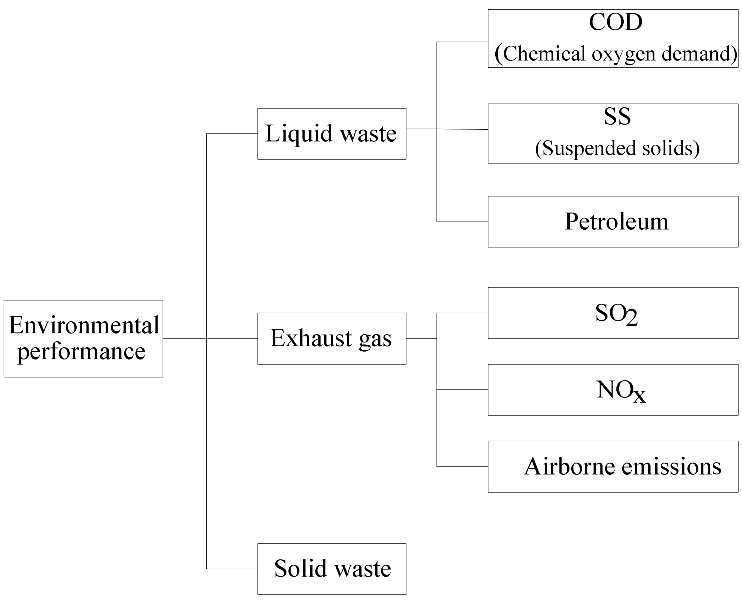

Fig. 3. Environmental performance measurements.

Table 1. Average consistencies of random matrices (the random index – *RI* values).

Size	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Cleaner production standard for Iron and steel industry [15] indicates that the reference value for COD (chemical oxygen demand) is 0.2 kg/t per steel, thus u_r may be set to 0.2 kg/t per steel.

Environmental Performance Evaluation Model

In the formulation of a multiple criteria evaluation problem, a very common approach is to combine different measurements into a single one using a weighting scheme. Such a weighting scheme can be difficult to develop since measurements often have widely disparate units (e.g. kg/t, liter, and kilogram); moreover, the relative importance of the decision criteria may differ among decision makers.

Once the criteria/measurements have been normalized, appropriate weights for different criteria/measurements need be determined. Appropriate weights for different quantities may be obtained by a variety of techniques, one of which is the analytical hierarchy process (AHP). AHP utilizes pair-wise comparisons for a set of criteria/measures to judge the relative importance of one criterion/measure to another.

In assessing the relative importance of one criterion to another, Saaty [16] suggested the use of a 9-point scale to transform the verbal judgments into numerical quantities representing the values of a_{ij}. The entries a_{ij} are governed by the following rules: $a_{ij}>0$; $a_{ij}=1/a_{ij}$. If the two criteria are equally important, then the relative importance is assigned a value of 1. If criterion i is twice as important as criterion j, then the relative importance, a_{ij}, is assigned a value of 2.0. If criterion i has one-fifth the importance of criterion j, then aij is set equal to 0.2. A judgmental matrix, denoted as *A*, will be formed using the comparisons. Because of the above rules, the judgmental matrix *A* is a positive reciprocal pairwise comparison matrix.

Once the judgment matrix of comparisons of criteria with respect to the goal is available, the weights of criteria can be obtained and the consistency of the judgments should be determined.

The weights associated with each criterion are calculated by geometric mean GM_i. The geometric mean can be expressed as follows:

$$GM_i = \left[\prod_{j=1}^{n} a_{ij}\right]^{1/n} \tag{2}$$

...where, n=1, 2, 3, ... i.

Then the geometric mean is normalized in order to obtain the relative weight, w_i, of each criterion. The normalized weight can be expressed as follows:

$$w_i = \frac{GM_i}{\sum_{i=1}^{n} GM_i} \tag{3}$$

The consistency of the judgment matrix can be determined by a measurement called the consistency ratio (*CR*), defined as:

$$CR = \frac{CI}{RI} \tag{4}$$

...where *CI* is called the consistency index, and is calculated using the maximum eigenvalue λ_{max} [17]. *CI* can be represented as follows:

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \tag{5}$$

...where n is the size of a comparison matrix.

RI is named the random index. The *RI* values for matrices of different sizes are shown in Table 1.

If *CR* of the matrix is higher, it means that the input judgments are not consistent, and hence are not reliable. In general, a consistency ratio of 0.10 or less is considered acceptable. If the value is higher, the judgments may not be reliable and have to be elicited again.

With the normalized values and weights available, the environmental performance score for the steelmaking process can be calculated as follows:

$$S = \sum_{i=1}^{3} b_i \sum_{j=1}^{t} d_j q_{ij} \quad i = 1,2,3 \quad j = 1,2,\cdots,t \tag{6}$$

...where b_i is the weight placed on i^{th} criterion (e.g. liquid waste), d_j is the weight placed on j^{th} measure (e.g. COD) within the ith criterion, and q_{ij} is the normalized value for the j^{th} measure for the i^{th} criterion. The following conditions must be met for the weights:

$$\sum_{i=1}^{3} b_i = 1 \quad \text{and} \quad \sum_{j=1}^{t} d_j = 1 \tag{7}$$

The sum of multiplied normalized values and weights across all of the criteria/measurements represents the overall score for environmental performance, and the score with larger number indicates better performance due to the normalizing method.

Table 2. Data of environmental emissions and reference values.

	Liquid waste (kg/t steel)			Exhaust gas (kg/t steel)			Solid waste (t/t steel)
	COD	SS	Petroleum	SO_2	NO_x	Dust	
A	0.060	0.023	0.0018	2.417	0.312	0.44	0.549
B	0.165	0.077	0.0024	3.312	0.254	0.893	1.215
C	0.106	0.071	0.0051	2.502	0.585	0.633	1.386
u_r	0.2	0.5	0.005	1.0	0.5	0.5	1.0

Illustrative Example

To illustrate the method for environmental performance evaluation, the steelmaking processes of three iron and steelmaking companies located in China were considered.

Company A is a big iron and steel joint venture with an annual output of 3,000×10^4 tons. Company A is in the domestic leading position by the introduction of new technology and equipment. Company B is a small-sized steel company with an annual output of 300×10^4 tons. The overall technology of company B is relatively outdated, and its resource consumption and waste emissions were serious. Company C is a middle-sized enterprise, having an annual output of 1,000×10^4 tons. All the processes consist of a coke plant, a sinter plant, blast furnace, basic oxygen furnace, and continuous casting. The starting point for the production of steel is the smelting of iron ore in a blast furnace, which uses coal in the form of coke to reduce iron ore to molten iron. Molten iron is converted into a range of applications in a basic oxygen furnace (BOF), which uses the rapid injection of oxygen to remove excess carbon and silicon in the iron. Liquid steel at over 1,600ºC is then cast into different cross-sectional shapes before passing through a series of finishing mills to give its final dimensions and mechanical properties.

Data of various environment emissions can be collected by using an input/output (I/O) diagram, which is an effective tool to describe the inputs and outputs that relate to a process [18]. In principle, there are two approaches for securing these data. One approach is to collect actual data on environmental emissions per one ton of liquid steel. A second approach is to utilize the data from the published technical literature, e.g. "China Steel Yearbook 2011" [19]. Of course, these data have either been based on or validated with actual process data.

All the environmental emission data for the process of the three companies were gathered, as shown in Table 2. The table also shows the ur values, which were defined either by the company or Chinese standard HJ/T 318-2006 and DB37/ 990 – 2008.

Once the data collections were completed, the normalized values for these measures can be calculated by Eq. (1), as shown in Table 3. Attention then shifted to identifying the relative importance of the environmental criteria/measures.

Based on the survey of experts opinions, we got the results of criteria (liquid waste, exhaust gas, and solid waste) pair-wise comparisons using a proportional scale. And the matrix is shown as follows:

$$B = \begin{bmatrix} 1 & 3 & 5 \\ 1/3 & 1 & 3 \\ 1/5 & 1/3 & 1 \end{bmatrix}$$

Calculating the largest eigenvalue of matrix B and its corresponding eigenvectors, the weights of criteria including liquid waste, exhaust gas, and solid waste are [0.64, 0.26, 0.1].

Table 3. Evaluating results for environmental performance.

Criterion	Weight	Measure	Weight	Score		
				A	B	C
Liquid waste	0.64	COD	0.53	3.33	1.21	1.89
		SS	0.33	21.74	6.49	7.04
		Petroleum	0.14	2.78	2.08	0.98
Exhaust gas	0.26	SO_2	0.58	0.41	0.30	0.40
		NO_x	0.31	1.60	1.97	0.85
		Dust	0.11	1.14	0.56	0.79
Solid waste	0.1			1.82	0.82	0.72
			Total score	6.38	2.27	3.35

The consistency index CR=0.037 <0.10, which confirms the consistency of the pairwise comparison matrix. Similarly, the weight of each measure within the criterion can be calculated as shown in Table 3.

With the normalized values and weights for the criteria/measures available, scores for the environmental performance of the steelmaking process were calculated by Eq.(6). These scores are shown in the rightmost column of Table 3.

In examining the results of this analysis, the scores for A and C are bigger than B; this indicates that from an environmental perspective, the environmental performance of A and C are better than B. In addition, results indicate that the large scale company (A) employing advanced technology has the best environmental performance of the three companies studied. On the basis of conducted analysis we found that the integrated environmental index can effectively reveal the environmental status of the steelmaking process. This could be a motivation to continuously upgrade environmental performance on the indicators, so as to perform better on this integrated index.

Conclusions

Environmental performance evaluation can be served as a decision-supporting tool to improve process performance. A proper representation of environmental impact is a hard task. The goal of this paper is to develop an integrated environmental index that will help process designers screen continuous environmental improvement opportunities for steelmaking.

Three steelmaking companies are used as the illustrative case study, and the AHP procedure is presented. The results suggested that the environmentally friendly processes could be obtained by technology innovation. It should be noted that process environmental performance evaluation remains an ongoing topic. More work of uncertainty and variation associated with the assessment index will be beneficial. It should also be noted that the conclusions for comparison were limited to the processing stage.

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